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IMPROVING WHEELED VEHICLE WATER SPEED

BY MEANS OF WHEEL SHROUDING

By

Anthony J. Rymiszewski

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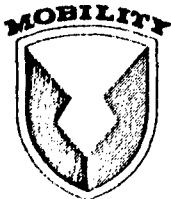
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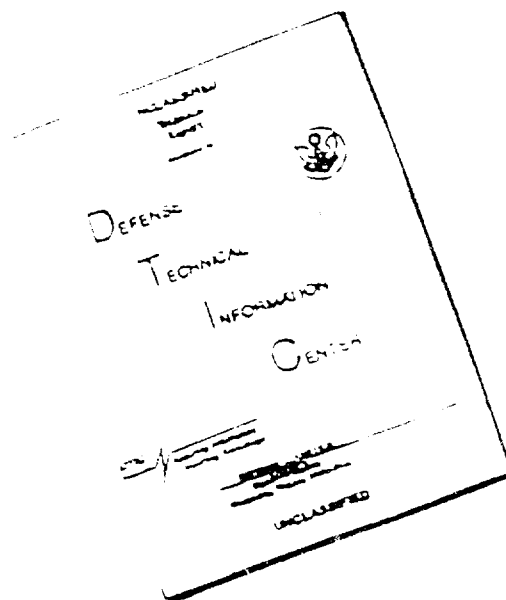
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To determine the potential of improving wheeled vehicle water speed by means of wheel shrouding.

It was found that wheel shrouding can improve vehicle speed appreciably when properly designed.

14. KEY WORDS Wheeled vehicles Vehicle water speed Vehicle wheel shrouding Amphibious vehicles Vehicle floatability Vehible water speed studies Wheel-water forces	LINK A		LINK B		LINK C	
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OBJECTIVE

Investigate the potential of improving wheeled vehicle water speed by means of wheel shrouding.

RESULTS

Three wheel shroud configurations differing in geometric design and flow control were experimentally analyzed in the Land Locomotion River Simulator facility using a self-propelled, one-eighth, scale model of the Truck, Cargo, 5 ton, 8x8, XM-453. Model vehicle test data is presented graphically and clearly shows the improvement in water speed obtained with each shrouding configuration tested.

CONCLUSIONS

Wheel shrouding can radically improve wheeled vehicle water speed when properly designed to control, destroy in part, and redirect the axial, radial, and tangential flows of the submerged, rotating wheels into useful thrust.

ADMINISTRATIVE INFORMATION

This program was supervised and conducted by the Land Locomotion Laboratory of ATAC, under D/A Project No. 597-01-006, Project No. 5016.11.04400.

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ABSTRACT

Presented in this report are experimental results of scale-model tests performed in the Land Locomotion Laboratory River Simulator to investigate the effects of wheel shrouding on wheeled vehicle water speed. This investigation was initiated to determine and analyze the swimming ability of wheeled vehicles resulting from wheel shrouding.

An unshrouded wheeled vehicle using its wheel drive system as its sole water propulsive agent was selected for this study. Experimental tests were performed using a self-propelled, one-eighth, scale model of the Truck, Cargo, 5-ton, 8x8, XM-453.

The model tests showed that wheel shroud design could radically improve water performance to a value of seventy percent above the maximum in the unshrouded condition. Also, it was shown that improper wheel shrouding and/or worn tire treads decrease the propelling forces of submerged wheels and limit a vehicle's water velocity well below the available "maximum."

ACKNOWLEDGEMENT

This study was performed under the supervision of Mr. W. L. Harrison, Jr., Chief of the Applied Land Locomotion Mechanics Section.

The author expresses appreciation to Mr. L. Moore, XM-453 vehicle project engineer, for providing the prototype data for the model-full size vehicle evaluation, and Mr. A. Messina for assisting with the experimental work.

DEFINITIONS

1. Floating - the ability of a vehicle to negotiate water obstacles without contact with the bottom. Self-propulsion while in the water is not implied in this definition.
2. Swimming - the ability of a vehicle to negotiate a water obstacle by propelling itself across, without contact with the bottom.
3. Amphibian - a vehicle designed to be both water craft and land vehicle.
4. Froude Number - ($F = \frac{V}{\sqrt{gL}}$) - ratio between inertial and gravitational forces in a fluid. It is composed of the velocity of the vehicle, the wetted length, and the acceleration of gravity.
5. Reynold Number - ($R_e = \frac{VL}{\nu}$) - ratio between inertial and frictional forces in a fluid. It contains the density and viscosity coefficient of the fluid medium, a characteristic length and its speed.
6. Shroud - any of various outer coverings designed to alter original vehicle geometry and/or water flow boundaries around a vehicle's wheels.
7. Side Plate - a smooth, thin, flat piece of any material of uniform thickness, used to control water flow by minimizing lateral boundary losses.
8. End Deflector - a smooth, curved surface developed to transform the lifting tangential forces of a rotating wheel to positive components of thrust.
9. Wheel Pants - a semi-circular, fixed, outer wheel covering used to redirect the negative momentum components of a rotating wheel to positive components of thrust.

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INTRODUCTION

During World War II and until recently, there were two types of military vehicles: land vehicles and amphibious vehicles. When a land vehicle encountered a river or a stream and there was no ford or bridge available, it was necessary to build a bridge of some sort or by-pass the river. However, vehicle designers opened a Pandora's box with the development of configurations that would provide either a swimming or floating capability in all but the smallest and largest vehicles. Once it had been proven that it was practical to build a 5-ton truck that could float, the user's appetite was whetted and what had been a desire became a requirement. As a result of this development, the designer has found that it is one thing to make a vehicle float but quite another to make it go somewhere other than at the whim of a river current.

An extensive effort has been directed to the investigation of hydrojets, paddles, and propellers to provide adequate water speed for both tracked and wheeled vehicles. However, in each of these cases water speed is obtained at the cost of added weight, complexity, and dollar expenditure for a component that will seldom be used during the life of a vehicle. It would seem much more practical to utilize the same propulsion system for water operation as for land operation; that is, wheels or tracks. The purpose of this paper

is to investigate the potential of the proper use of wheels in water operation using the same philosophy that has been applied to tracked vehicles.

Experience has shown that tracked vehicles which have the upper portion of their tracks out of the water develop higher speed than those having the complete track submerged. However, when the complete track is submerged, it has often been demonstrated that water speeds have been increased by limiting water flow around the return section of the track through the use of shrouding, fenders, or skirts. This technique seldom has been employed in the design of wheeled vehicles to improve water performance. This could partially account for the poor performance of wheeled vehicles when compared to that of tracked vehicles utilizing shrouds.

A swimming wheeled vehicle derives its propulsive thrust by accelerating the water surrounding the wheels.

It is surprising, therefore, that no real effort has been expended towards the development of a high-efficiency, simple means of using present wheel drive systems as sole water-propulsion forces. A literature search revealed that the behavior of a powered wheel, partially or completely submerged in water, has not been described so that one might accurately predict the thrust developed by even a simple, unshrouded wheel.

An attempt to derive a general wheel propulsion theory from a purely mathematical viewpoint requires the application of three-dimensional fluid flow theory to a short rotating cylinder submerged at variable depths and inclosed by variable boundary conditions^{1,2}. Attempts to derive such a theory have been unsuccessful. Some of the mathematical difficulties are in the solution of the Navier-Stokes equations, which include non-linear inertia terms that cannot be linearized³. In view of these difficulties, it was decided that it would be worthwhile to develop a simplified theoretical framework to guide an experimental study and to suggest modifications which would substantially improve the water speed of a wheeled vehicle.

The objective of the experimental work reported herein was to investigate the possibility of increasing the water speed of wheel-driven vehicles by means of wheel shrouding. To analyze this problem experimentally, a one-eighth scale model of the XM-453 was constructed. Self-propelled model tests were performed in the straight-channel test section of the Land Locomotion Laboratory River Simulator which has a depth of four feet; a width of six feet; and a test length of eighty-four feet.

The XM-453, 5 ton, Truck, chosen for this study is an experimental swimming cargo carrier capable of inland water operation. This is an eight wheel drive vehicle with

16.00 x 20 low profile, non-directional, military tires. It has an overall length of 269 inches, width of 96 inches, height of 112 inches (reducible to 79 inches), and a maximum loaded displacement of 26,000 pounds. When operating in water and fully loaded, the test vehicle assumes a longitudinal trim of 1-3/4 degrees stern down. Based on the results of vehicle performance tests conducted in Maryland's Conowingo Dam Basin, the test vehicle can obtain a maximum water velocity of 2.1 miles per hour when driven in high transfer, transmission in third gear, and all eight wheels providing propulsion⁴.

The problem at hand was to determine if the measured maximum water velocity of the XM-453 is the "optimum" that can be obtained when using only wheels for propulsion; and, if this is not the "optimum" condition, would wheel shrouds increase or decrease its water velocity? Also, if wheel shrouding will increase the propulsive efficiency of a wheel, what is the practical maximum vehicle water velocity one may expect from a given wheel shroud design?

This report presents the results of a preliminary investigation of wheel shrouding based on the evaluation of three practical and economical wheel shroud configurations.

THEORETICAL ANALYSIS

A. SHIP MODEL THEORY AND VEHICLES:

It is well known that results from a model ship test are applicable only to the performance of the prototype if the flow around the model is similar to that around the prototype^{5,6}. Similarity is achieved when the relative magnitudes of inertia, gravity and viscous forces are identical in the two cases. The ratio of inertia to gravity forces in a moving fluid is commonly described by means of the Froude Number:

$$F = \frac{V}{\sqrt{gL}}$$

where V is the vehicle speed, g the acceleration due to gravity, and L the wetted length. When a model is run at the same Froude Number as the full-sized ship, the surface wave patterns are the same shape and are dimensionally in scale. The ratio of inertia to viscous forces is described by the Reynolds Number:

$$R_e = \frac{VL}{\nu}$$

where ν is the kinematic viscosity of the fluid⁷. The usefulness of Reynolds Number lies in the fact that its value is a guide to the type of flow which can be expected around a body moving completely submerged in a fluid.

Ideally, then, a model test should be carried out with

both the Froude and Reynolds Numbers equal to those of the prototype, that is:

$$\frac{V_M}{\sqrt{gL_M}} = \frac{V_p}{\sqrt{gL_p}} \quad \text{and} \quad \frac{V_M L_M}{\nu_M} = \frac{V_p L_p}{\nu_p}$$

$$\text{or} \quad \frac{V_M}{V_p} = \frac{\sqrt{L_M}}{\sqrt{L_p}} \quad \text{and} \quad \frac{V_M}{V_p} = \frac{L_p \nu_M}{L_M \nu_p}$$

$$\text{which requires that} \quad \frac{\sqrt{L_M}}{\sqrt{L_p}} = \frac{L_p \nu_M}{L_M \nu_p}$$

$$\text{and hence that} \quad \frac{V_M}{V_p} = f^{3/2}$$

where f is the scale factor.

Thus, the model tests must be carried out in a special fluid whose kinematic viscosity bears a particular relation to that of the water in which the prototype floats. Unfortunately there is no fluid with suitable properties for use with models of a reasonably small scale factor. In principle, therefore, accurate model tests of ships and vehicles cannot be carried out.

The total motion resistance of a ship or vehicle can be broken down into the following five parts^{8,9}:

1. Surface Wavemaking Resistance: The vehicle generates a surface wave system around it and in its wake as motion takes place. These waves are a function of the

Froude Number at which the vehicle operates and the form and loading of the vehicle. The magnitude of this system increases with the n 'th power of speed. For vehicles with box-like shapes, blunt bows, and small length-width ratios, this is likely to be the most important component of motion resistance.

2. Skin Friction Resistance: This resistance is due to the friction of the water upon the submerged wetted surfaces of the vehicle. Skin friction is a function of the Reynolds Number at which the vehicle operates and depends on the wetted area, nature and length of the wetted surface, water viscosity, water density, and the n 'th power of speed. Frictional resistance varies approximately as the 1.825 power of speed for a flat plate parallel to the flow direction; three-dimensional bodies will have other exponents¹⁰.

3. Eddymaking Resistance: Eddymaking resistance, in the form of vortex energy losses, is produced whenever accumulated low-pressure stagnant water is shed from the vehicle's surface corners. This resistance is also a function of the vehicle's Reynolds Number and can be reduced only by careful design of the vehicle's lines.

4. Appendage Resistance: Appendage resistance is an additive type of resistance dependent upon the Reynolds Numbers of individual axles, gas tanks, shafts, struts, wheels, wheel hubs, and other underbody components. Appendage resistance also varies as the n 'th power of speed and can be greatly reduced by inclosing the vehicle's underbody with a smooth contour.

5. Wind Resistance: Wind resistance is caused by air eddying across and through the vehicle's superstructure. This resistance is a function of the air Reynolds Number, wind direction, wind velocity, and superstructure design. Wind velocity is a minimum at the surface of the sea and increases rapidly with height. Naval architects estimate the wind resistance for ships operating at speeds below ten knots and in winds below ten knots to be less than three percent of the total motion resistance¹⁰. Since a land vehicle swimming in water has less superstructure than a ship and a much higher water resistance, it follows that air resistance can be neglected.

Luckily for the naval architects the skin, eddy-making, and appendage resistance of a normal ship are very small compared with the wavemaking resistance. Therefore,

the model tests are carried out at the same Froude Number and are used to predict wavemaking resistance. The other resistances are calculated from the dimensions and required speed of the ship using empirical data based on accumulated experience. It seems unreasonable to expect this technique to be applicable to a vehicle for which the Reynolds Number dependent resistances are likely to be at least equal to the wavemaking resistance. That this is true is suggested by the fact that a typical land vehicle has a resistance five to ten times that of a comparable boat⁸, and that the addition of a well-designed hull will not appreciably decrease the total resistance if the appendages are not covered.

A further major difficulty arises when the propulsion system is considered. It is normal ship practice to consider propulsion and resistance as two separate problems which are investigated by means of quite separate hull and propeller tests. This enables the hull tests to be carried out at the same Froude Number and the propeller tests at the same Reynolds Number, since in the latter case gravitational forces are negligible. Unfortunately, however, the wheel cannot be considered in isolation from the vehicle hull, because, as will be described later, it

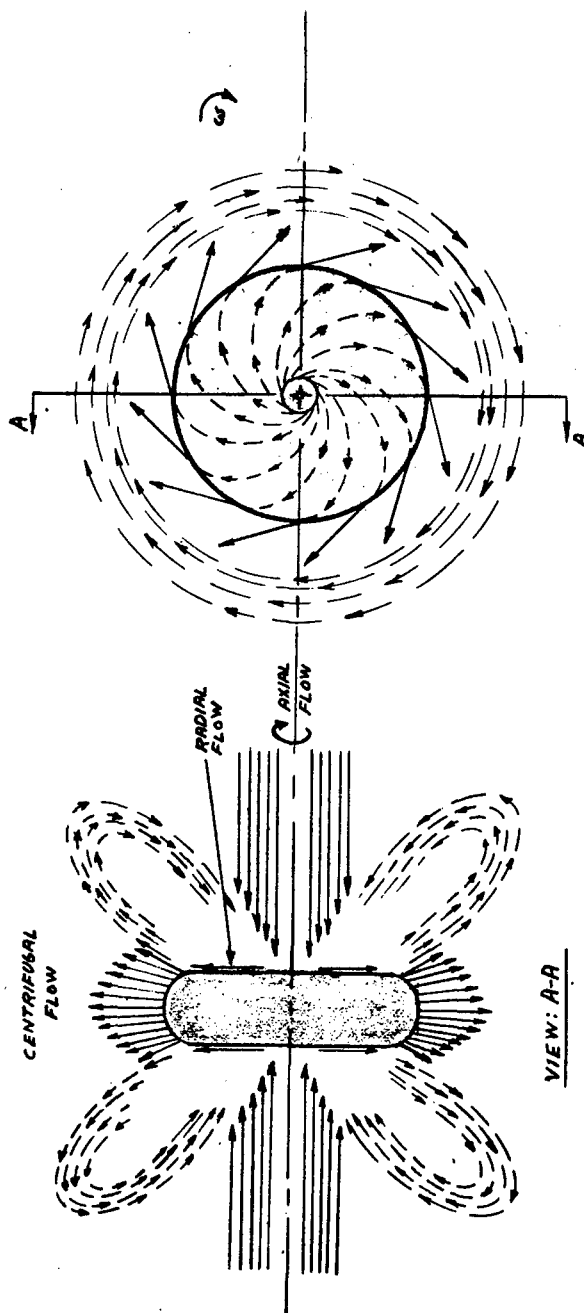
only exerts a propulsive effect because of its close association with the hull.

It was concluded that model testing is not likely to occupy the same position of importance in design development of swimming land vehicles that it has achieved for ships. On the one hand there are the theoretical difficulties described above, and on the other, the fact that several full size prototypes are a necessity for vehicles but an impossibility for ships. The improvement of vehicle swimming speed can easily be carried out using a full sized prototype and the simplest of experimental equipment.

B. THE MECHANICS OF WHEEL PROPULSION:

Figure 1, shows a smooth, thick disk rotating in a fluid in which it is deeply submerged. The two sides of the disk will drag fluid around by means of viscous forces and the tangential velocity acquired will give rise to centrifugal forces and, therefore, radial accelerations and velocities. The sides will then act as centrifugal pumps and cause circulatory flows parallel to the wheel axle on either side of the wheel. These two flow patterns will also swirl around in the direction of wheel rotation. Fluid in contact with the periphery of the wheel will be pumped outward and swirled around and replaced by part

of the flow up the disk sides.



Flow and Swirl of a Deeply Submerged Rotating Disk

Figure 1.

The flow system of Figure 1 is symmetrical about both the disk center line and the disk axle; and, therefore, there can be no resultant force on the disk, only a torque. Energy is transferred from the disk to the fluid and dissipated as heat by means of viscous forces. The addition of vanes to the sides of the disk and tread bars to the periphery will increase the flow and the torque. This system cannot provide any propulsive force because of its symmetry.

It then follows that in order to obtain thrust in a particular radial direction, the symmetry must be destroyed in such a way that flow and, therefore, fluid momentum is reduced in the opposite direction.

Figure 2, shows fluid leaving the wheel at exit angles of 0, 45, and 90°, which covers more than the greatest possible range. It is probable that angles between 0 and 45° are most likely. The lower diagrams show the distribution of horizontal component velocities around the wheel, and are therefore also representative of the distribution of horizontal forces exerted by the fluid on the rim. It can be seen that in each case the distribution is such that there is no resultant horizontal force.

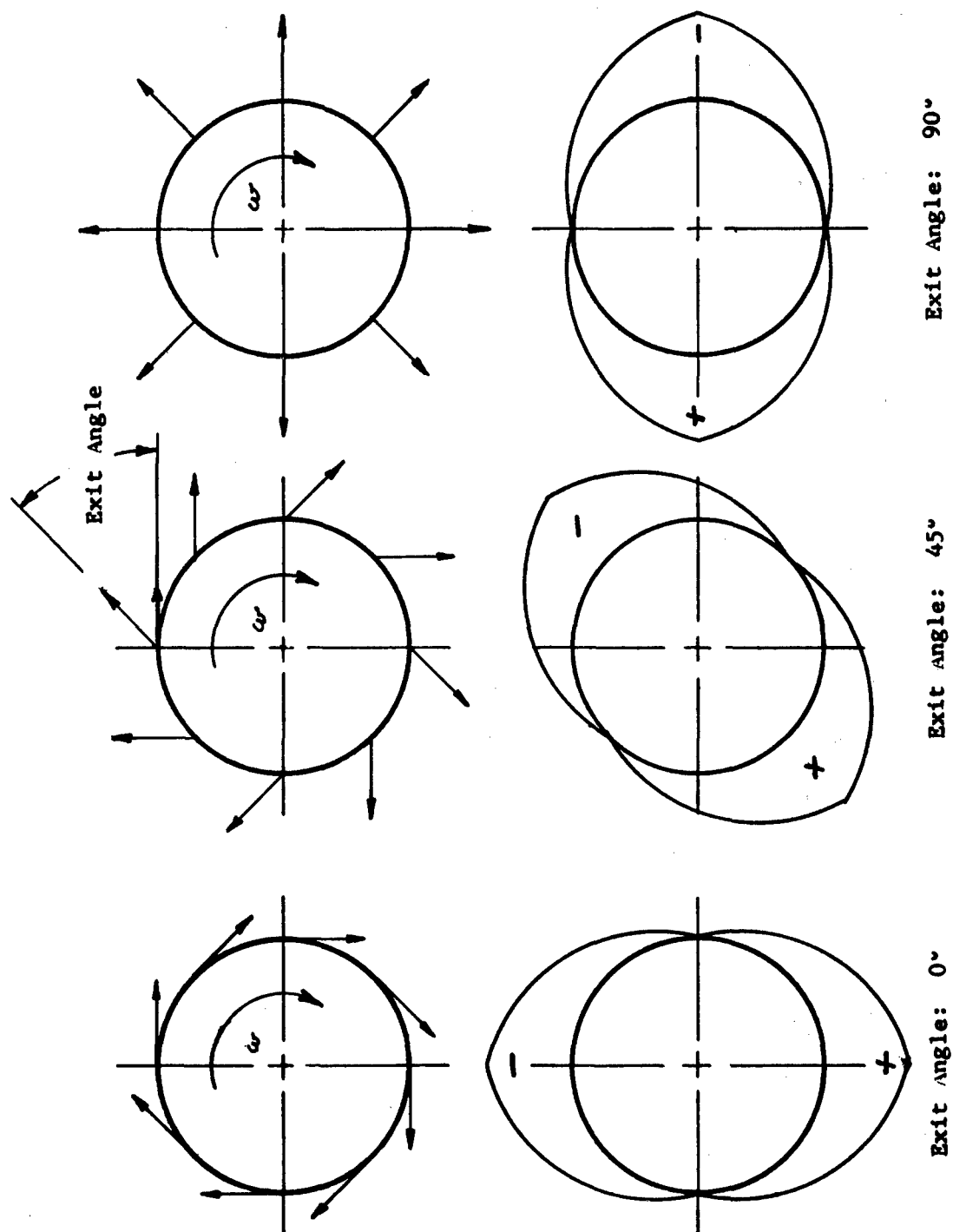


Figure 2: Distribution of Horizontal Fluid Momentum Around a Deeply Submerged Wheel for Exit Angles between 0 and 90°.

A net horizontal thrust can be achieved by suppressing part of the flow in that region of the disk with negative momentum. This would obviously be achieved by placing a flat surface above the disk, because flow would be diminished along all those paths that are affected by the pressure losses involved in the changes in direction of flow caused by the surface. The thrust would be zero for exit angles of 90° and increase as the angle diminished, but would always be positive. The thrust would increase as the surface was brought nearer to the wheel, and also by bending it around the top of the wheel as in a wheel arch. A similar effect would be achieved by a vertical wall on one or both sides of the wheels extending down to the axle centers. It appears that this is a simple explanation for the thrust obtained from a wheel fixed to a vehicle, and it is useful because it can be used to suggest means of augmenting this thrust.

Figure 3, shows the same picture for vertical exit velocity components, from which it is clear that the isolated wheel is completely balanced. Shrouding the upper parts of the wheel will evidently have the effect of producing a net lift in all cases. This is, of course, a useful force as it slightly reduces the draft and the resistance.

An alternative approach to that of reducing flow in the forward direction is to redirect the flow rearwards by means

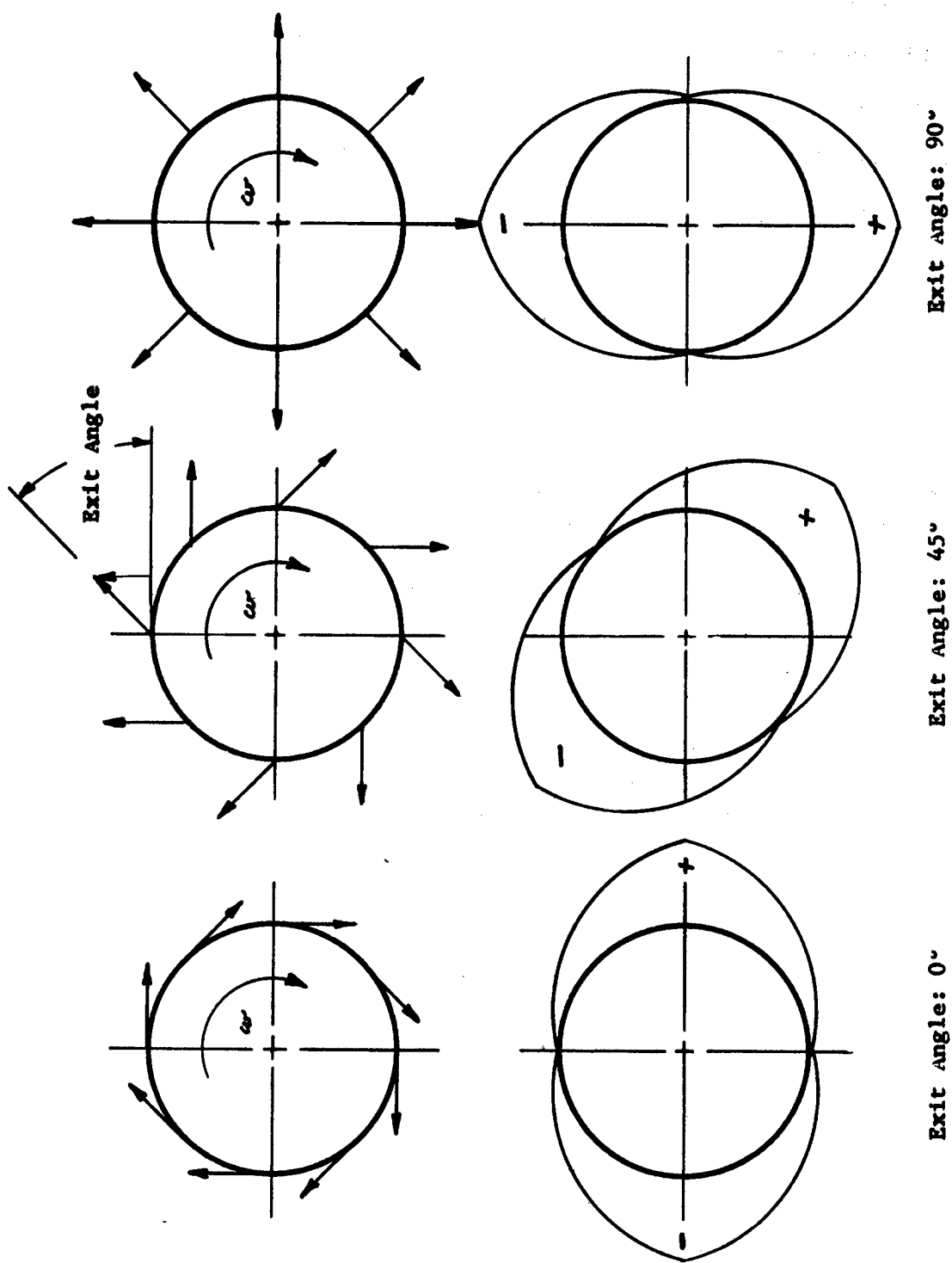
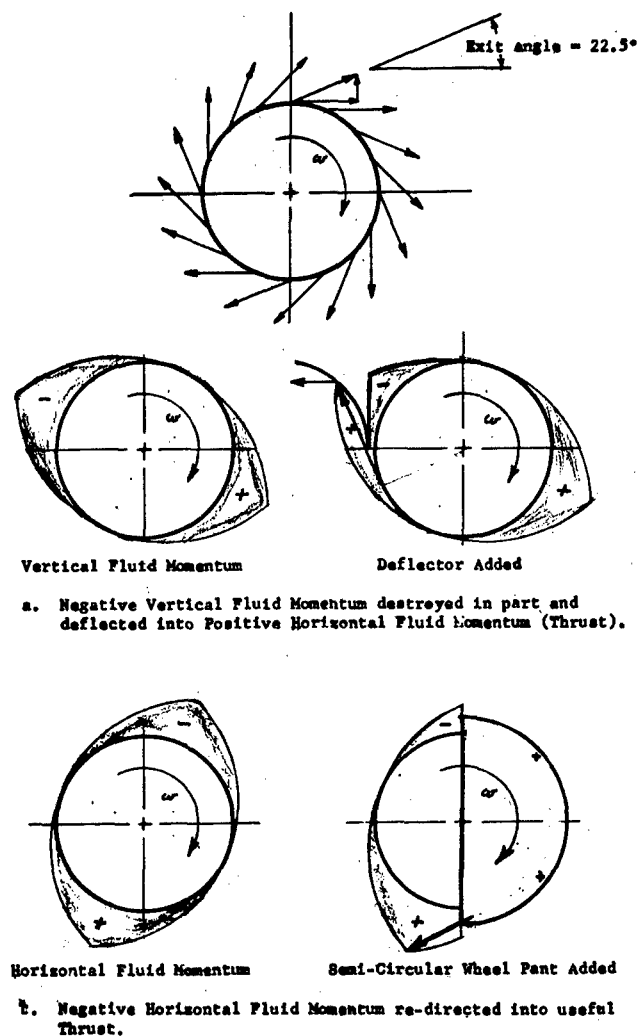


Figure 3: Distribution of Vertical Fluid Momentum Around a Deeply Submerged Wheel for Exit Angles between 0 and 90°.

of guide vanes fitted to the vehicle body. Figure 4, shows two such possibilities; the deflectors have the merit of low cost and simplicity, and could remain in place on the vehicle at all times. The semi-circular parts could be the vehicle's normal wheel arches which would be rotated forward through an angle of 90° after it enters the water.



Changing Fluid Momentum with Guide Vanes

Figure 4.

TEST APPARATUS AND PROCEDURE

Figure 5, shows a one-eighth scale model of the 5-ton Cargo Truck selected for this study. The model was statically balanced at 51 pounds to correspond to a full size displacement of 26,000 pounds. Axle loads on the front and rear bogies were 43.5 and 56.5 percent, respectively. This simulated a maximum rear axle loading condition and resulted in a model trim of two degrees stern down. Self-propulsion and eight-wheel drive were provided by a variable speed D.C. motor. The dimensions of the water basin used were: 84-foot length, 6-foot width, and 4-foot depth. A wire cable was used to guide the model through the center of the test tank.

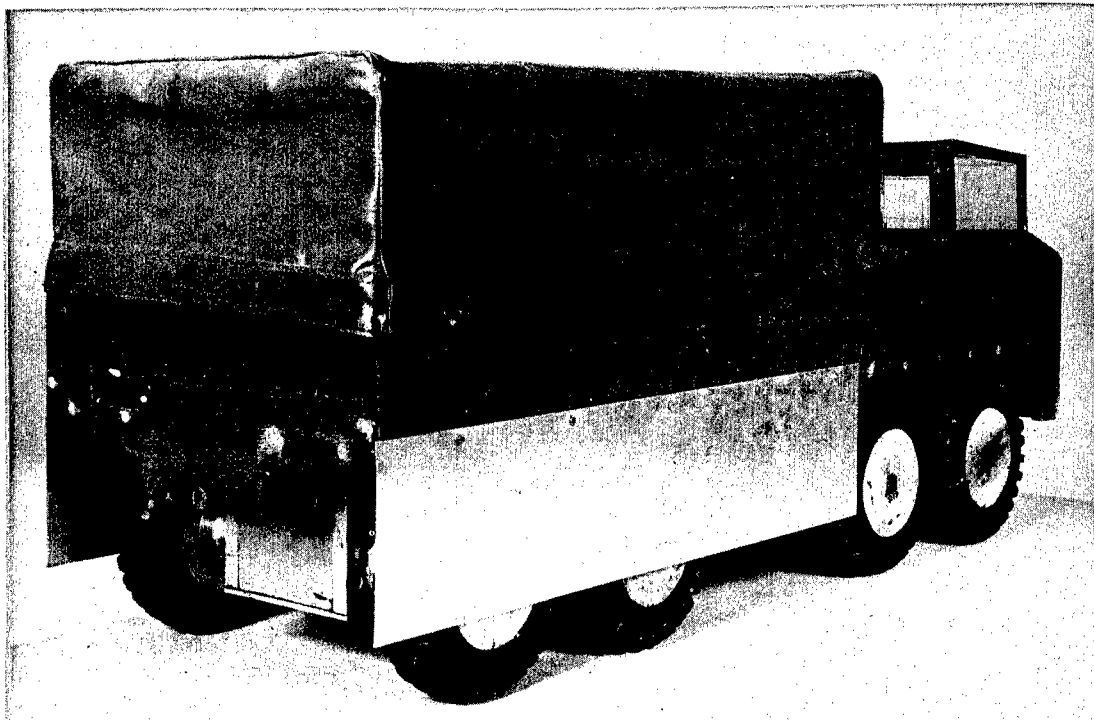


Figure 5.

Three wheel shroud configurations differing in geometrical shape and size were tested. These were arbitrarily titled: rectangular side plates, deflectors, and semi-circular wheel pants. The rectangular side plates were chosen to restrict the flow input to the top portion of the wheel. Curved deflectors were designed to deflect the lifting forces obtained at the rear of the wheel into useful thrust. Semi-circular wheel pants were used to increase propulsion efficiency by simulating the volute-impeller characteristics of a pump. Combinations of these designs for a "maximum" performance increase were also evaluated. All the shrouds tested were fixed to the model and were not free to rotate with the wheels. Additional tests involved evaluating the effect of tire tread on wheel propulsion.

A typical test run consisted of allowing the model to accelerate for twenty feet to reach a constant velocity, timing the next forty feet, and recording the corresponding wheel speed which was precisely recorded in terms of wattage input to the motor.

Each shroud configuration was run over a series of wheel speeds, from 0 to 296 RPM, and the results plotted as "Vehicle Speed versus Wheel Speed". This gave a range of vehicle Froude Numbers against wheel Reynolds Numbers.

Wheel speed was limited to 296 RPM because this condition satisfied Froude's law of comparison wherein the maximum unshrouded speed of the model simulated the maximum unshrouded speed of the full size cargo truck:

$$V_M = \sqrt{8} \frac{V_P}{\sqrt{8}} = \frac{3.1(\text{ft/sec})}{\sqrt{8}} = 1.1 \text{ ft/sec.}$$

The Froude Number corresponding to this velocity is:

$$F_M = F_P = \frac{3.1 (\text{ft/sec})}{\sqrt{32.2(\text{ft/sec}^2) \times 22(\text{ft})}} = 0.116$$

The corresponding Reynolds Numbers of the model and prototype are:

$$R_{e_M} = \frac{VL}{\nu} = \frac{1.1(\text{ft/sec}) \times 22/8(\text{ft})}{1.08 \times 10^{-5}(\text{ft}^2/\text{sec})} = 2.8 \times 10^5$$

$$\text{and } R_{e_P} = \frac{3.1(\text{ft/sec}) \times 22(\text{ft})}{1.08 \times 10^{-5}(\text{ft}^2/\text{sec})} = 6.3 \times 10^6.$$

Similarly, the wheel Reynolds Numbers for the model and the prototype at this maximum unshrouded speed were very different, being:

$$R_{e(\text{prototype wheel})} = \frac{VL}{\nu} = \frac{\pi D^2 N}{60 \nu} = \frac{\pi(4)^2 (250)}{60(1.08 \times 10^{-5})} = 1.93 \times 10^7$$

$$\text{and } R_{e(\text{model wheel})} = \frac{\pi(\frac{4}{8})^2 (296)}{60(1.08 \times 10^{-5})} = 3.57 \times 10^5$$

It is important to note that dynamic similarity cannot be achieved because there are three dimensionless groups involved, only one of which can be made similar between model and prototype during any one series of tests. To satisfy Reynolds law of comparison between model and prototype requires a model velocity of $8\sqrt{8} \times 3.1$ (ft/sec) equal to 70 ft/sec. Likewise, equal wheel Reynolds Number can only be achieved if model wheel RPM is $(8)^2 \times 250$ (prototype wheel RPM) equal to 16,000 RPM. Thus these two seemingly simple requirements are difficult, if not impossible, to fulfill in practice.

TEST RESULTS

1. Rectangular Side Plate Shrouding: Using rectangular plates along the entire length of the vehicle and varying only the depth of wheel diameter covered resulted in the family of curves shown in Figure 6. Typical side plate shroudings used are shown in the upper left corner of the figure. With the entire length of the vehicle covered and the entire wheel diameter covered, vehicle water velocity decreased approximately 16% below the unshrouded condition. With the entire length of the vehicle covered and only $5/8$ of the wheel diameter covered, an increase of 22% in vehicular water speed was obtained. This condition is independent

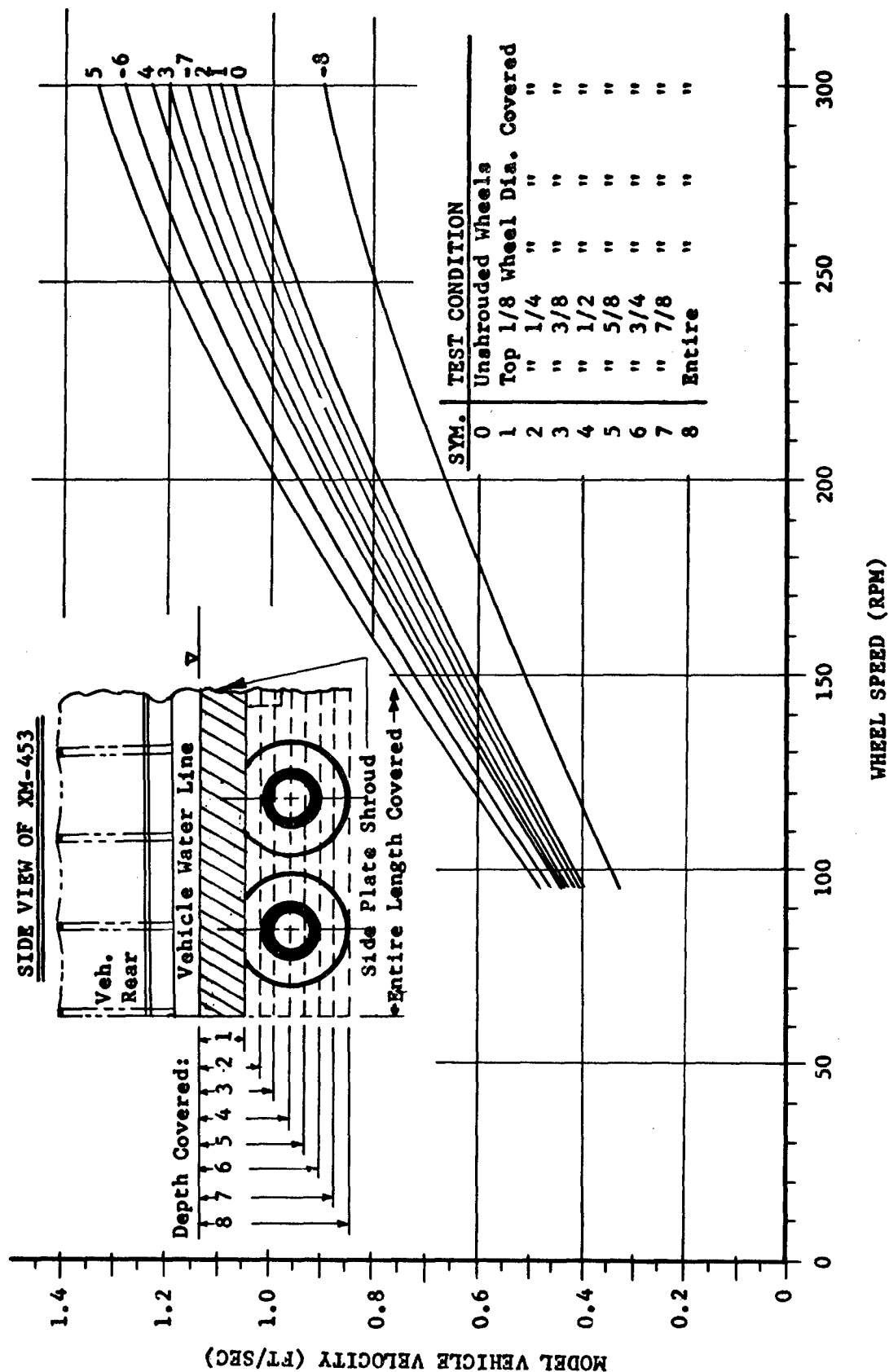


Figure 6: Full Length - Variable Depth Side Plate Shroud Results

of wheel RPM as shown in Figure 7, and is the maximum increase that can be obtained when restricting the flow into the upper half of the wheel. Decreasing the length of vehicle covered to 55% (rear to front) as shown in Figure 5, and maintaining the 5/8 wheel diameter dimension, results in a more practical arrangement that does not restrict steering and still gives an increase of 13% above the unshrouded condition.

2. Deflector Shrouding: The use of a curved shroud at the rear of the wheel to deflect the upward, lifting, forces into horizontal thrust was very effective. Two such deflectors, one on each of the rear wheels, provided a 13% increase in water speed. Using deflectors on both rear wheels and both intermediate front axle wheels, as shown in Figure 8, provided a 32% increase in vehicle water speed. No increase in water speed could be obtained when deflectors were added to either the front axle wheels or the intermediate rear axle wheels. This is logical since the forces involved actually tend to cancel each other in this eddy region.

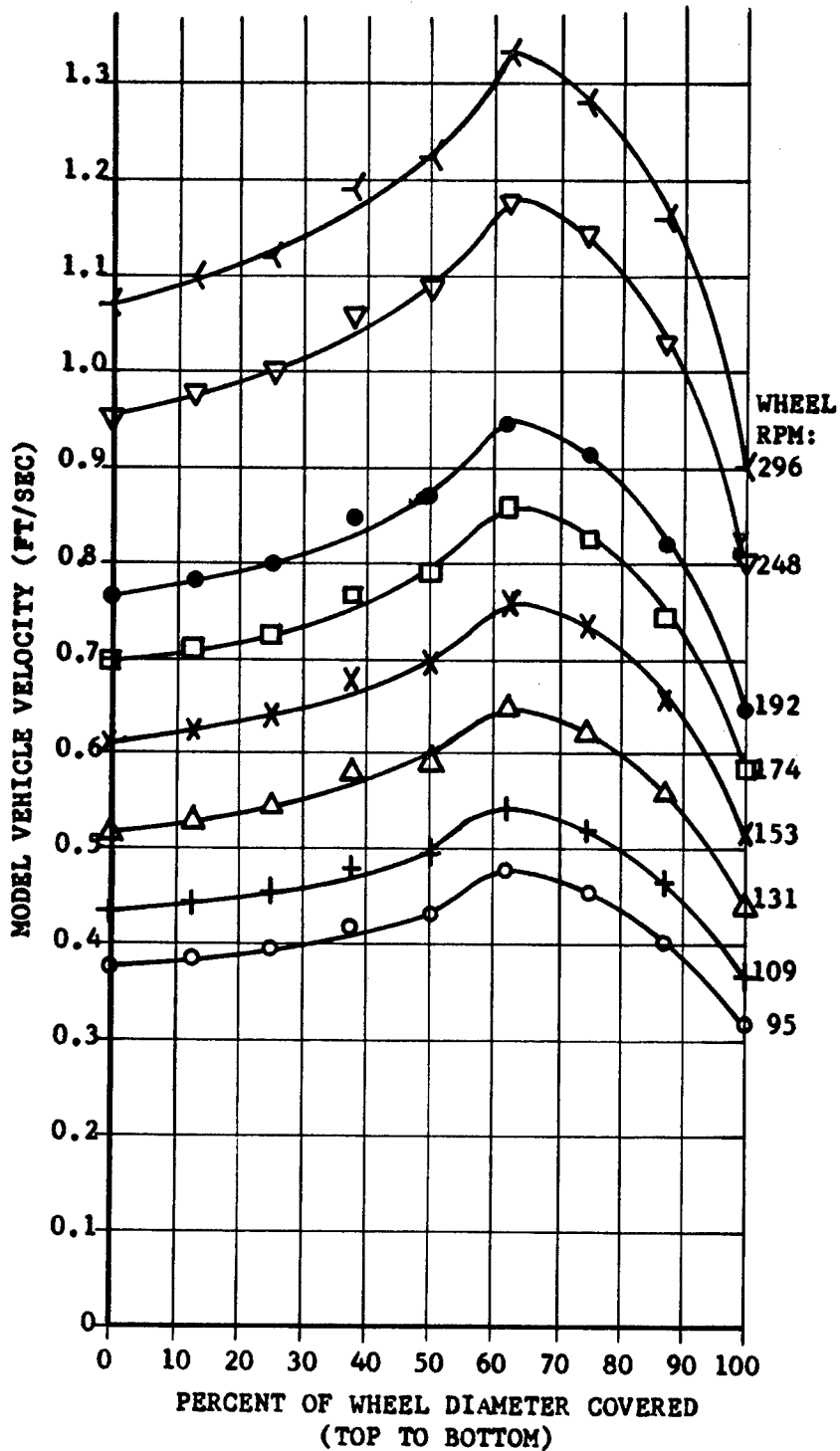


Figure 7: Effect of Wheel Speed when Increasing the Depth of a Full Length Side Plate Shroud.

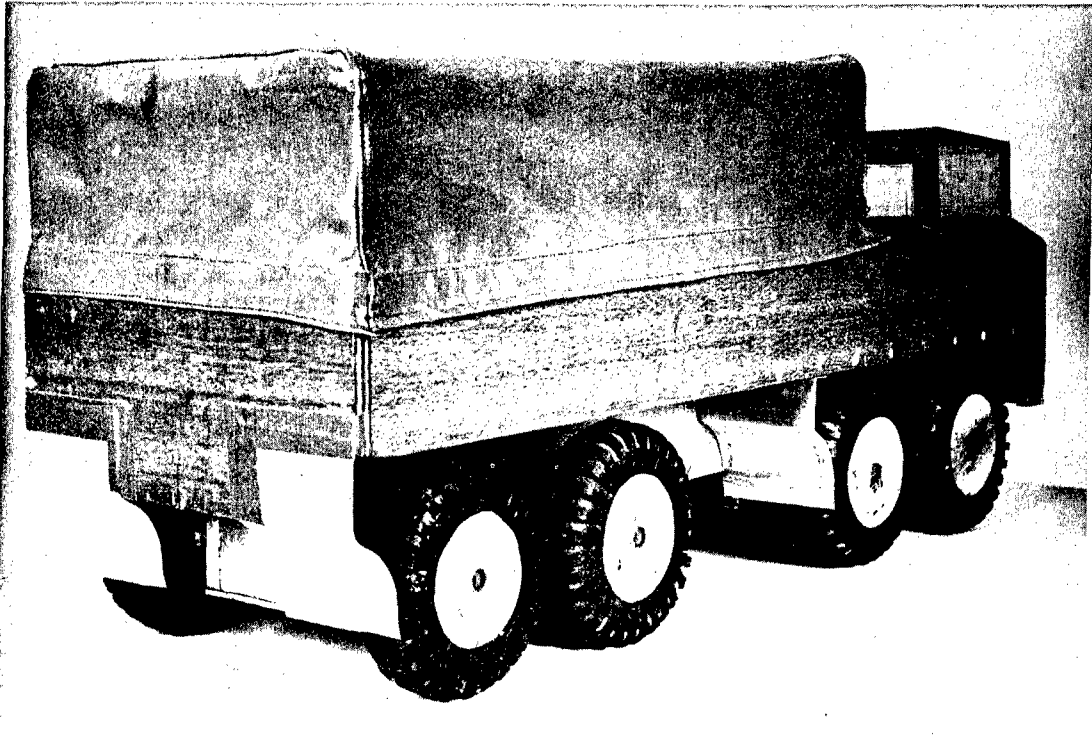


Figure 8.

3. Semi-Circular Wheel Pant Shrouding: A semi-circular housing covering the forward half of the wheel provides for greater control of flow than either the side plate shroud or the force deflectors. (Figure 9). Two of these wheel pants on the rear wheels only provided a 13% increase in water speed. Covering the four rear wheels provided a 32% increase in vehicle water speed. A 42% increase in vehicle water speed was

obtained when the six rear wheels were housed in these pants. With all eight wheels covered, an increase of 51% above the unshrouded condition was obtained.

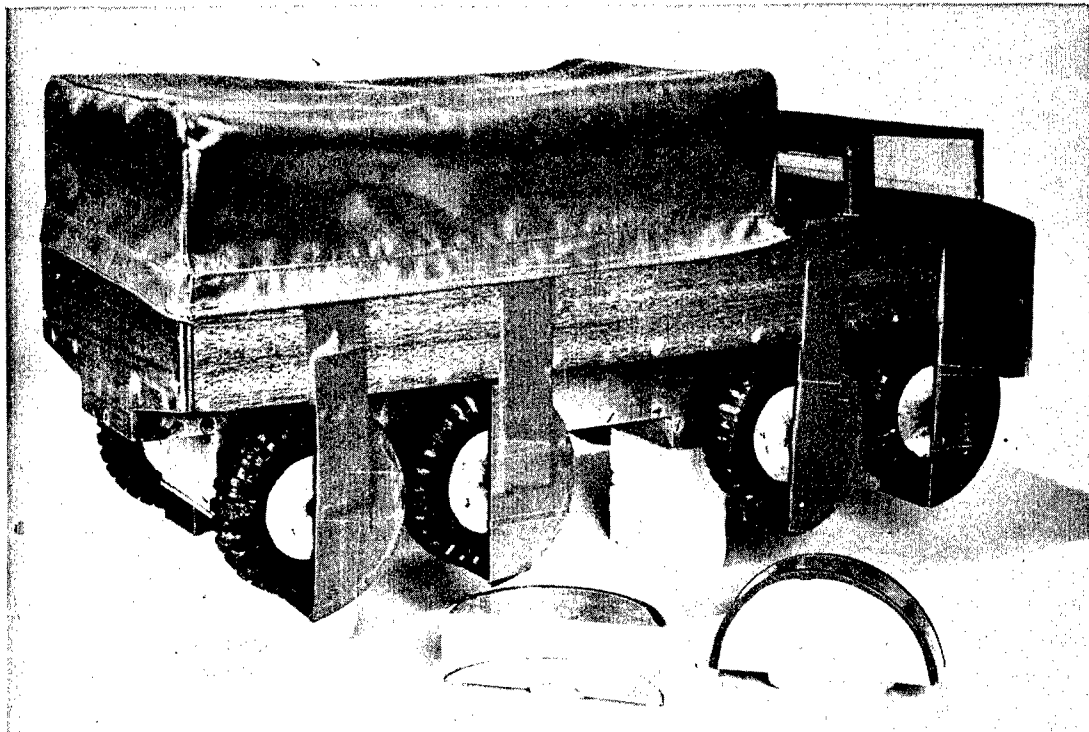


Figure 9.

4. Combined Shrouding Results: The combination of the half length-half depth side plate shrouds and the four deflectors is a simple and inexpensive addition to the vehicle that could be left permanently in place without detracting at all from its performance on land. It gives a worthwhile speed increase of about one-third. This gain was more than doubled by the more complex arrangement obtained by the combination of half length-half depth side plate shroud, four deflectors, and six semi-circular wheel pants, (Figure 10) giving a total speed increase of 70%.

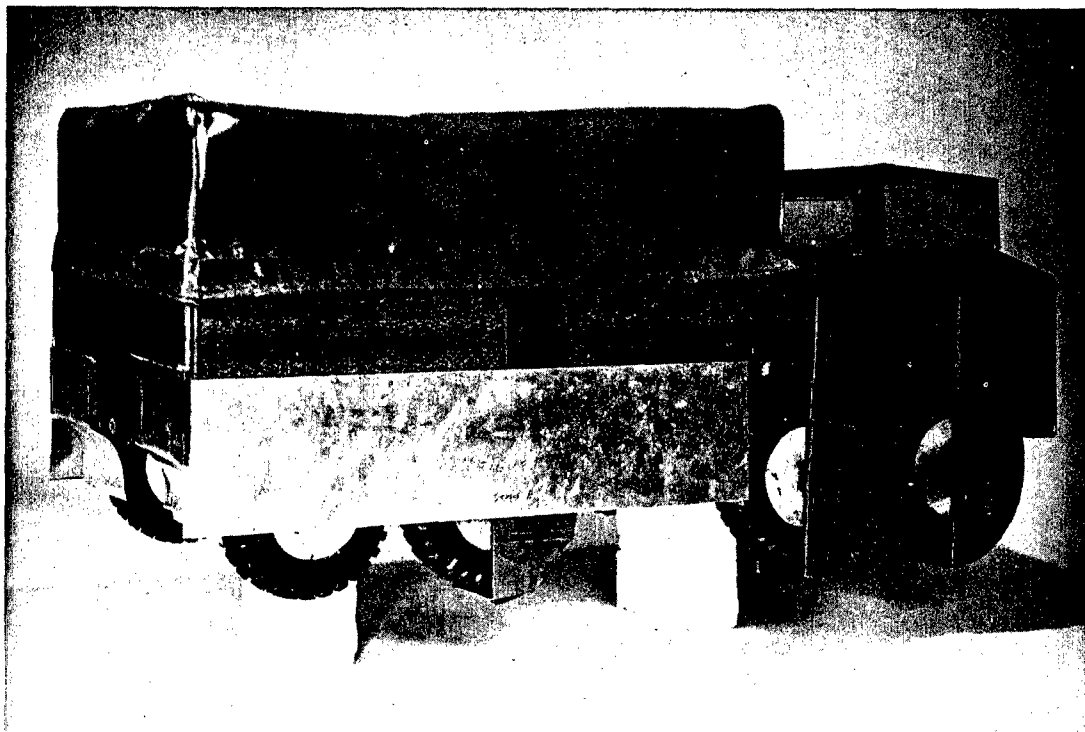


Figure 10.

Using Froude's method of model-prototype comparisons it is indicated that a prototype speed of 5.3 ft./sec. or 3.6 miles per hour, could be achieved with this "optimum" shroud configuration. The results of the various combinations tested were plotted as a family of performance curves and are shown in Figure 11. These curves clearly show that wheel shrouding can radically improve wheeled vehicle water speed when properly designed to control, destroy in part, and redirect the axial, radial, and tangential flows of the submerged, rotating wheels into useful thrust.

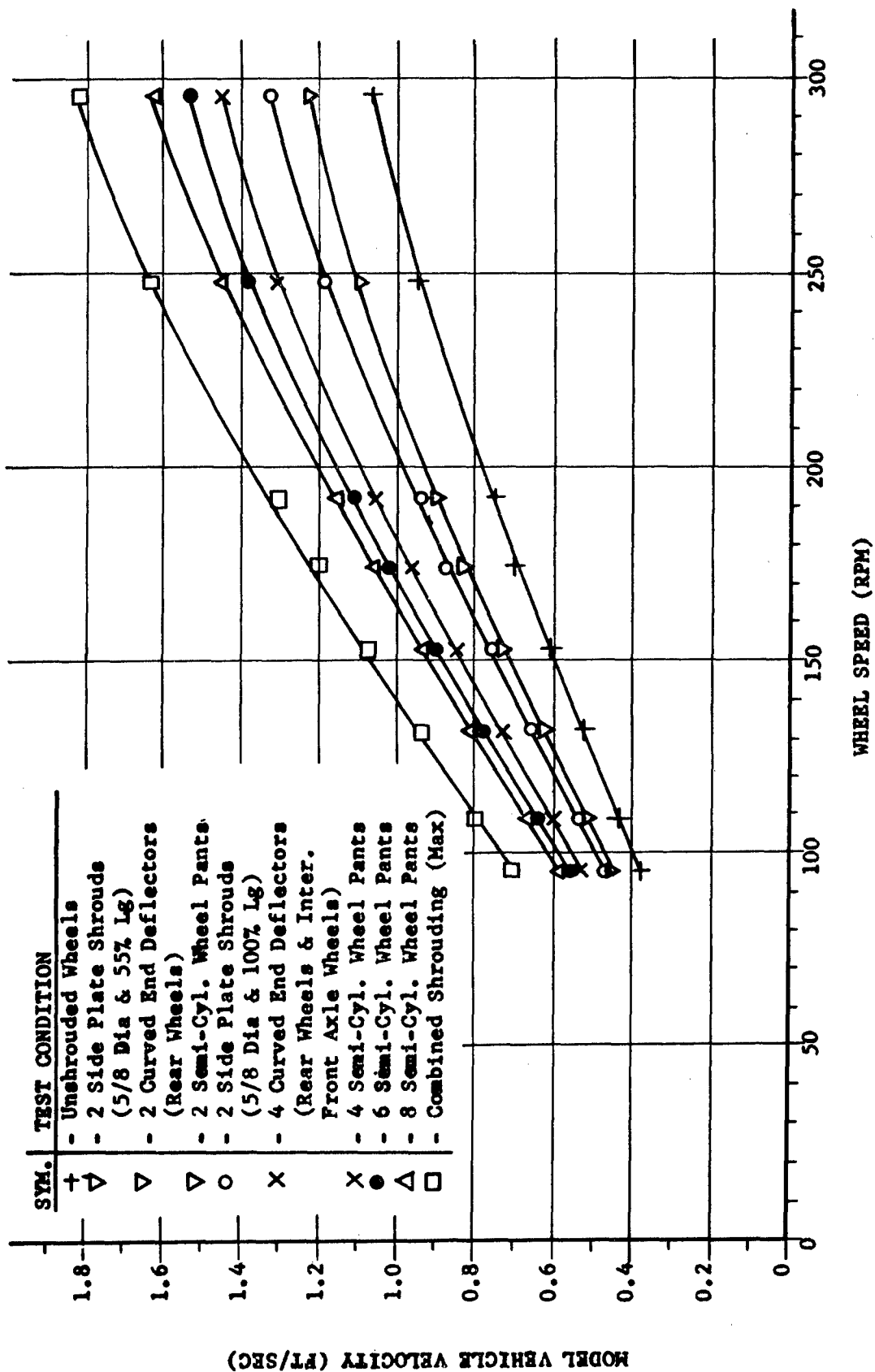


Figure 11: Increased Model Velocity through Shrouding Plotted as a Family of Curves.

5. Effect of Tire Tread: The wheels were fitted with models of the standard military tire which has a small tread pattern with short radial lugs on the side which turn through 90° to form straight transverse lugs across each half of the periphery of the tire. From the standpoint of impeller design, these tires are little more than smooth disks, and a set of tests were carried out to see how important the treads were.

Worn tires were simulated by covering the periphery only with tape. Figure 12, shows that this reduced the performance by more than half in both the most effectively shrouded and the unshrouded case. These test curves strongly suggest that considerably greater gains in speed above the combined shrouding results, could be achieved by either designing tire and wheel to be more effective impellers or by adding impellers to the wheels for water operation.

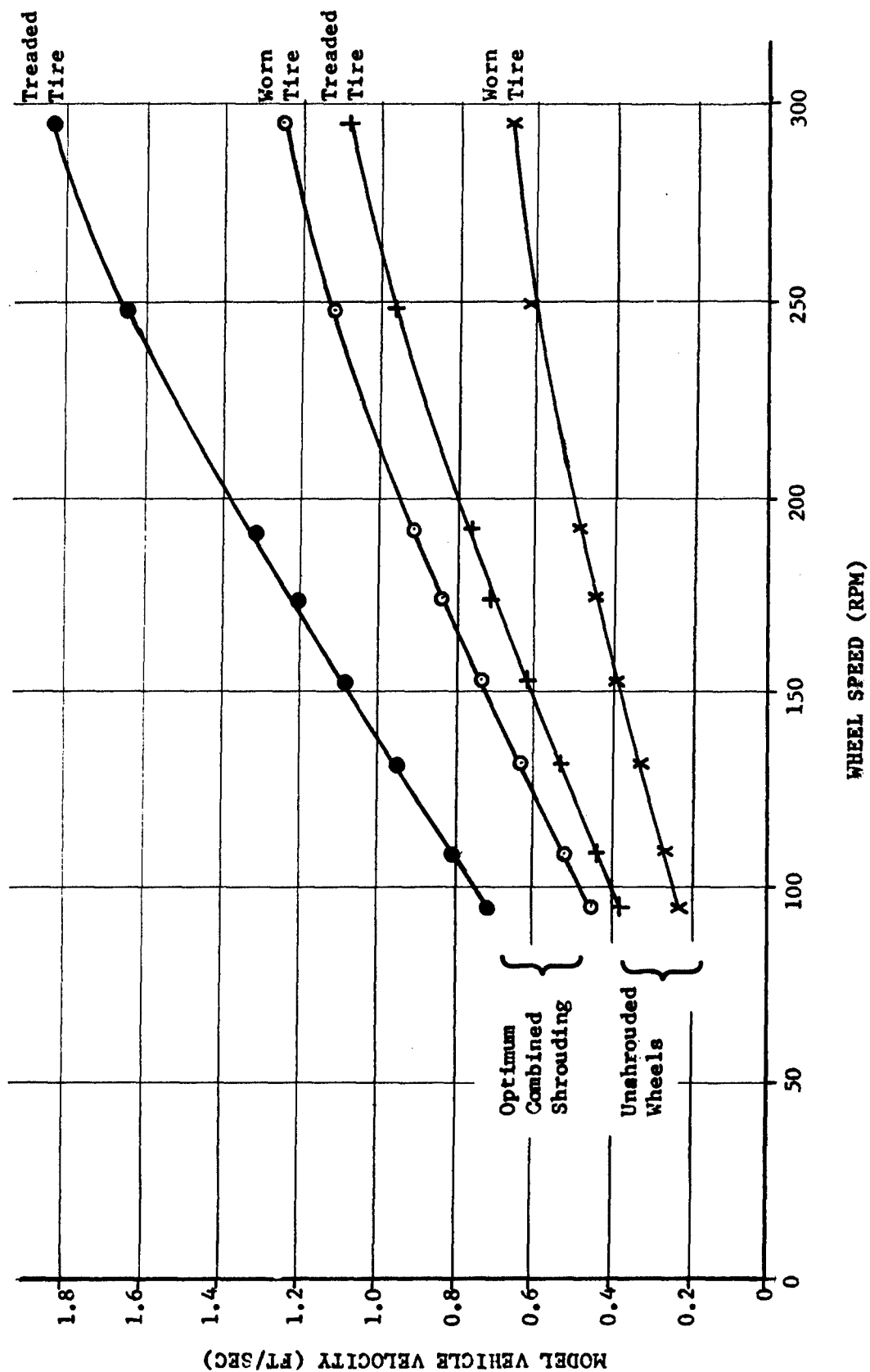


Figure 12: Effect of Tire Tread on Water Propulsion

CONCLUSIONS

The following conclusions are based on the scale model test results of the XM-453 Truck:

a. General Conclusions:

1. Wheeled vehicles using their wheel drive system as the sole water propulsive agent can attain increased water velocities through properly designed wheel shrouds.
2. Properly designed wheel shrouds control the axial, radial, and tangential flows of a completely submerged wheel; thereby, increasing the available wheel thrust by diminishing the flow in the negative momentum or backward region, and by altering the direction of flow in these regions.
3. Wheeled vehicle swimming speed is basically limited by the smoothness of the wheels which are incapable of transmitting a large proportion of the engine power to the water. The "maximum" speed increase obtainable through wheel shrouding can be further augmented by increasing the effectiveness of the wheels as impellers.

b. Specific Conclusions Concerning the XM-453:

1. Restricting the axial flow into the top of the wheel, the backward reaction region, with a

rectangular side plate shroud design covering the entire vehicle length and $5/8$ of the wheel diameter increases forward velocity approximately 22% above the unshrouded condition.

2. Restricting the axial flow into the bottom of the wheel, the forward reaction region, with a rectangular side plate shroud design covering the entire vehicle length and entire wheel diameter decreases forward velocity approximately 16% below the unshrouded condition.
3. Rectangular side plate shrouds covering 55% of the vehicle length (rear to front) and $5/8$ of the wheel diameter resulted in a practical arrangement that does not restrict steering and still gives an increase of approximately 13% above the unshrouded condition.
4. The use of two deflector shrouds, one on each rear wheel, to deflect the upward lifting forces at the rear of the wheel into horizontal thrust increases forward velocity approximately 13% above the unshrouded condition. An increase of 32% was obtained by attaching two more deflector shrouds, one each on the intermediate front axle

wheels. No further increase can be obtained by adding deflector shrouds to either the front axle wheels or the intermediate rear axle wheels.

5. The use of semi-circular wheel pant shrouds to redirect the negative momentum flows into useful thrust gave the following results regardless of location:

- (a) Two increased forward velocity approximately 13% above the unshrouded condition.
- (b) Four: approximately 32% increase.
- (c) Six: approximately 42% increase.
- (d) Eight: approximately 51% increase.

6. The maximum increase that could be obtained with the shroud design tested was 70% above the unshrouded condition. This was accomplished through combined shrouding using the following:

- (a) Two rectangular side plate shrouds: 55% vehicle length and $5/8$ wheel diameter covered.
- (b) Four deflector shrouds: one each on the intermediate front axle wheels and the rear axle wheels.
- (c) Six semi-circular wheel pant shrouds: one each on the six front wheels. Note: covering all eight wheels did not appreciably increase the forward speed.

RECOMMENDATIONS

1. It is recommended that prototype vehicle shrouding tests of the XM-453 Truck be performed using the three geometrically different shroud designs evaluated in this report, and that a study be initiated to correlate the developed scale model theory and experimental results with the full scale vehicle test results.
2. It is recommended that further study of the wheel propulsion phenomenon be continued both theoretically and experimentally and include an evaluation of the actual propulsive forces developed by the wheels at various peripheral speeds.
3. It is finally recommended that a tire study be initiated to increase the effectiveness of the wheels as impellers by providing a tread-impeller design capable of transmitting a larger proportion of the engine power to the water.

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Report No. 8088, pp-35
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Presented in this report are experimental results of scale-model tests performed in the Land Locomotion Laboratory River Simulator to investigate the effects of wheel shrouding on wheeled vehicle water speed. This investigation was initiated to determine and analyze the swimming ability of wheeled vehicles resulting from wheel shrouding.

An unshrouded wheeled vehicle using its wheel drive system as its sole water propulsive agent was selected for this study. Experimental tests were performed using a self-propelled, one-eighth, scale model of the Truck, Cargo, 5-ton, Bx8, XM-453.

The model tests showed that wheel shroud design could radically improve water performance to a value of seventy percent above the maximum in the unshrouded condition. Also, it was shown that improper wheel shrouding and/or worn tire treads decrease the propelling forces of submerged wheels and limit a vehicles water velocity well below the available maximum.

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